

REPORT DOCUMENTATION PAGE

AFRL-SR-BL-TR-99-

38

Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing the collection of information, sending the information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1204, Arlington, VA 22202-4302, and to the Office of Management and Budget, Paperwork Reduction Project (0106).

0106

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this collection of
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1. AGENCY USE ONLY (Leave blank)

2. REPORT DATE

3. REPORT TYPE AND DATES COVERED

Final 01 Nov 97 to 30 Sep 98

4. TITLE AND SUBTITLE

(T&E) Real Time Predictive Flutter Analysis and Continuous Parameter Identification of Accelerating Aircraft

5. FUNDING NUMBERS

61102F

2304/KS

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REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

AFOSR/NM
801 North Randolph Street RM732
Arlington, VA 22203-1977

10. SPONSORING/MONITORING
AGENCY REPORT NUMBER

11. SUPPLEMENTARY NOTES

12a. DISTRIBUTION AVAILABILITY STATEMENT

APPROVAL FOR PUBLIC RELEASE; DISTRIBUTION UNLIMITED

12b. DISTRIBUTION CODE

13. ABSTRACT (Maximum 200 words)

1. PROGRESS REPORT

This is a four-part final report on the research supported by the Air Force Office of Scientific Research Center under Grant F49620-98-1-0112, Real Time Predictive Flutter Analysis and Continuous Parameter Identification of Accelerating Aircraft.

14. SUBJECT TERMS

15. NUMBER OF PAGES

16. PRICE CODE

17. SECURITY CLASSIFICATION
OF REPORT

UNCLASSIFIED

18. SECURITY CLASSIFICATION
OF THIS PAGE

UNCLASSIFIED

19. SECURITY CLASSIFICATION
OF ABSTRACT

UNCLASSIFIED

20. LIMITATION OF
ABSTRACT

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**AIR FORCE OFFICE OF SCIENTIFIC RESEARCH
GRANT F49620-98-1-0112
Final Report - February 1999**

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SUMMARY

This is a four-part final report on the research supported by the Air Force Office of Scientific Research Center under Grant F49620-98-1-0112, **Real Time Predictive Flutter Analysis and Continuous Parameter Identification of Accelerating Aircraft**.

1. Motivations and research plan

Flutter clearance, which is part of any new aircraft or fighter weapon system development, is a lengthy and tedious process from both computational and flight testing viewpoints. An automated approach to flutter clearance that increases flight safety and reduces flight hours requires as a stepping stone the development of a real time flutter prediction capability. Such a fast analysis tool can be designed if the coupled fluid/structure aeroelastic system is represented by a simplified mathematical model that can be quickly adapted to changes in flight atmospheric conditions, aircraft mass distribution (weapon systems), fuel loading, and Mach number, and if the current parallel processing technology is exploited.

Furthermore, flight testing is always required to establish the flutter envelope of an aircraft. The traditional method for determining such an envelope uses test data extracted from the vibration response of the aircraft at fixed flight conditions. The aircraft is first trimmed to a specific flight condition (Mach number and dynamic pressure), then its aeroelastic response is deliberately excited by applying an input to a flight control surface. The frequency and damping of the excited aeroelastic response are typically extracted from

the vibration data. By repeating this test at many flight conditions, the flutter envelope can be determined. Such a traditional approach requires that the aeroelastic response be measured at many different flight conditions. This often requires a large number of flight test hours, a process which not only costs money but also exposes test pilots to proportionately increased risk. However, this test procedure can be expedited if data collected from continuously varying flight conditions can be used to extract the needed flutter damping and frequency values from an accelerating flight profile. In that case, it may be possible to greatly reduce the number of flight hours required for establishing the flutter envelope.

The Air Force Flight Test Center at the Edwards Air Force Base (AFB) has expressed great interest in the above two problems, and therefore we have proposed to conduct a three-year research effort in real time flutter analysis, and the continuous parameter identification of an accelerating aircraft. More specifically, we have proposed to develop a simplified flutter analysis method that can be run real time to provide predictive frequency and damping values for maneuvers as flown. The enabling technology of such a real time flutter analysis capability is a formulation of the aeroelastic problem that allows, among other things, partial pre-solutions and the usage of parallel processing.

We have also proposed to develop a parameter identification technique that can be used to extract frequency and damping values of an aircraft that is continuously accelerating. This technique is based on an arbitrary Lagrangian/Eulerian formulation for simulating accelerated flow problems and on windowing techniques.

Here, we report on both efforts outlined above and which have been conducted in collaboration with the researchers and engineers of the Air Force Flight Test Center at the Edwards AFB.

2. Results todate

During the fiscal year 1998, we have obtained the following results, all of which pertain to our long-term objectives described above.

2.1. A CFD based method for solving aeroelastic eigen problems in all flight regimes

In a first step, we have designed a linearized CFD method for computing an arbitrary number of eigen solutions of a given aeroelastic problem. Our method is based on the re-engineering of a three-way coupled formulation previously developed for the solution in the time domain of nonlinear transient aeroelastic problems. It is applicable in the subsonic, transonic, and supersonic flow regimes, and independently from the frequency or damping level of the target aeroelastic modes. It is based on the computation of the complex eigen solution of a carefully linearized fluid/structure interaction problem, relies on the inverse orthogonal iteration algorithm, and reutilizes existing unsteady flow solvers.

We have validated this method with the flutter analysis of the AGARD Wing 445.6 for which experimental data is available.

In a second step, we have improved the convergence of our linearized CFD method by enhancing the convergence of the inverse orthogonal iteration algorithm via the use of true second-order flow jacobians. We have simultaneously improved the convergence of our iterative solver applied to the solution of the underlying systems of equations. Both enhancements have allowed us to improve the overall CPU solution time of our method by a factor ranging between 4 and 10, depending on the given problem.

Some aspects of this specific progress are documented in the following reports, which have also been submitted and accepted for publication in archival journals:

M. Lesoinne and C. Farhat, "A CFD Based Method for Solving Aeroelastic Eigenproblems in all Flight Regimes," *Journal of Aircraft*, (submitted for publication).

M. Lesoinne, M. Sarkis, U. Hetmaniuk, and C. Farhat, "A Linearized Method for Extracting Eigen Solutions of Aeroelastic Systems," *Computer Methods in Applied Mechanics and Engineering*, (in press).

X.-C. Cai, C. Farhat and M. Sarkis, "A Minimum Overlap Restricted Additive Schwarz Preconditioner and Applications in 3D Flow Simulations," *Contemporary Mathematics*, Vol. 218, pp. 478-484 (1998).

2.2. Continuous parametric identification of an accelerating aeroelastic system

The traditional flutter testing approach implies a relatively large number of flight test hours, a process which is not only expensive, but also exposes test pilots to increased risks. One way to expedite this test procedure is to develop a method for expanding the flutter envelope of an aircraft that can use data collected from continuously varying flight conditions. By extracting the needed flutter damping and frequency values from an accelerating flight profile, it may be possible to substantially reduce the number of flight hours required for establishing the flutter envelope of an aircraft. However, we have determined that two fundamental issues must be addressed before a method for the continuous parametric identification of an accelerating aircraft can be developed.

The first issue deals with how the aeroelastic properties of an aircraft can be affected by a constant acceleration in a level flight or during maneuvering. In particular, is it possible to relate in a simple way the aeroelastic parameters measured in an accelerated flight to those measured in stabilized flight conditions? To the best of our knowledge, this issue has not yet been addressed in the literature.

The second issue is related to the fact that most if not all identification methods used in practice implicitly assume that the given aeroelastic system is linear and non-varying in time. Whether these methods can still be used to analyze accelerated flight data, or whether new methods are required for this purpose remains an open question.

During the first year of funding, we have addressed preliminary aspects of the above two issues by performing appropriate CFD based numerical simulations. More specifically,

we have considered a typical NACA 0012 wing section and investigated the effects of a horizontal acceleration on the aeroelastic response of this system. For this purpose, we had to upgrade our computational aeroelasticity capability to handle accelerated flight, which was by itself an interesting and rewarding research. We have reported on the aeroelastic results simulated in both cases of stabilized flight conditions and accelerated flight. We have compared these results and formulated preliminary conclusions regarding the theoretical feasibility of extracting the flutter envelope of an aircraft from an accelerated flight data.

This specific progress is documented in the following AIAA paper:

D. Rixen, C. Farhat, and L. Peterson, "Simulation of the Continuous Parametric Identification of an Accelerating Aeroelastic System," *37th Aerospace Sciences Meeting and Exhibit*, Reno, Nevada, January 12-15 (1999).

Motivated by our success for the NACA0012 airfoil, we have repeated our simulations of the continuous parameter identification of an accelerating aeroelastic system for a typical F16 wing section. We have designed this wing section from geometrical and structural data obtained from the Edwards AFB. The continuous parameter identification was simulated for the F16 typical wing section in accelerated flights with up to 0.05 Mach per second and for flight regimes extending from subsonic to supersonic. As shown in Figure 1, the aeroelastic parameters identified in accelerated flight are almost identical to those obtained in stabilized flight conditions. This work shows that the accelerated flight methodology is also applicable to a non-symmetric supersonic airfoil. In particular, the effectiveness of the accelerated flight approach remains good in the transonic region where the aeroelastic behaviour is highly non-linear. It was however not possible to match *perfectly* our numerical simulation results for the typical wing section with actual test results for the F16 (see Figure 1) because the available test data are for a loaded wing, whereas our typical wing model was derived from a clean wing model, and because the typical wing section approach is valid only for uniform, straight and high aspect ratio wings. However, the typical wing section properties can be tuned so that the numerical simulation results are closer to the flight test data (e.g. in Figure 2 we show the influence of the position of the elastic center). Further work will apply the accelerated flight methodology to a full 3-D aeroelastic model.

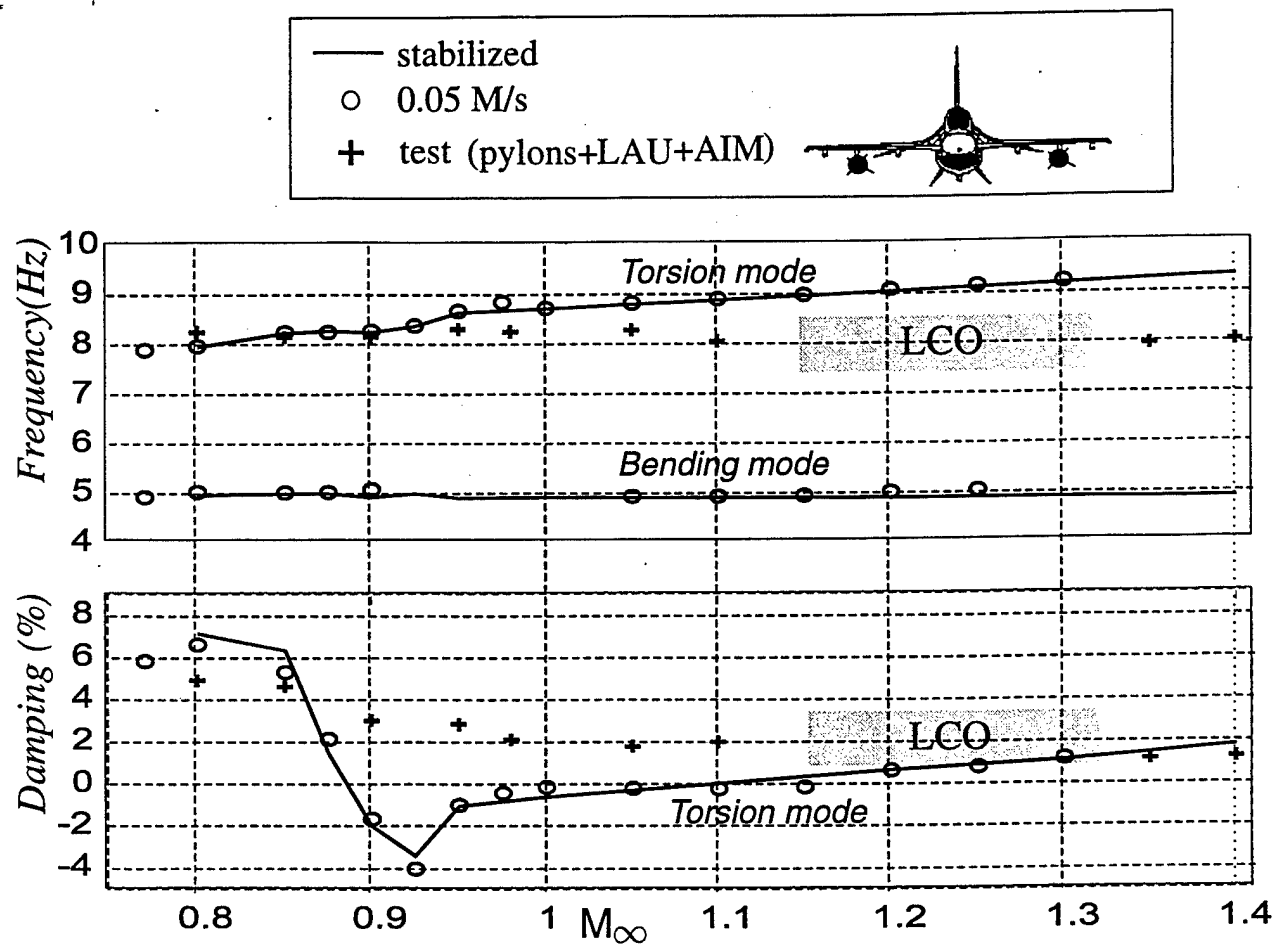


Figure 1. : identification on F16 typical wing section

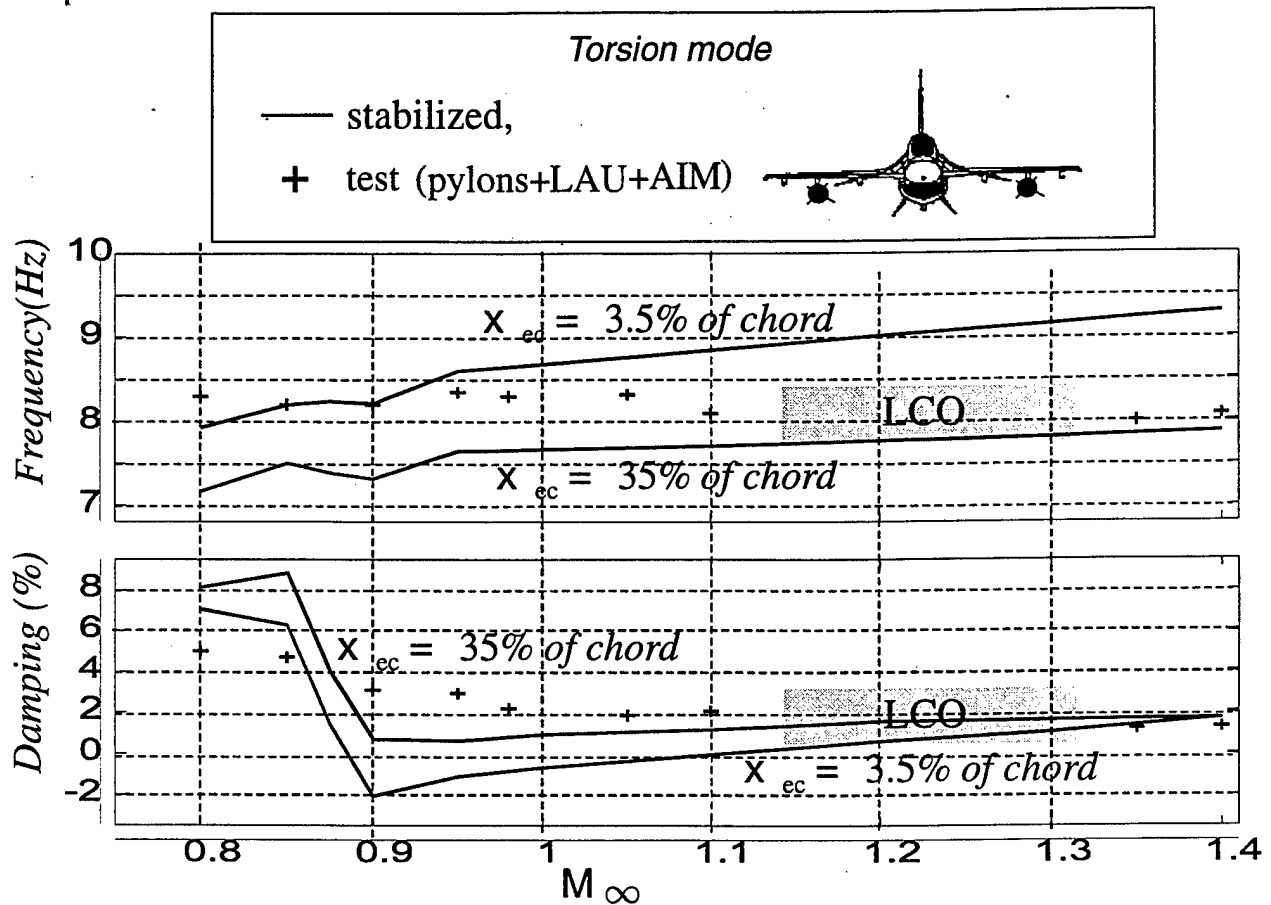


Figure 2. : model tuning

2.3. Design of an F16 advanced aeroelastic model

Because we envision applying our methods to an F16 fighter for which flight test data will be given to us by the Edwards AFB, we have acquired from Lockheed-Martin two different finite element models of an F16 aircraft version Block 50. The first model is a static one and therefore does not contain the mass distribution. The second model is a linear dynamic model which contains the needed mass information but is not adequate for stress analysis. We have began converting these models to our software modules, refining them for more advanced aeroelastic computations, and combining the best of their features to construct a unified and advanced aeroelastic dynamic finite element model.

2.4. Interaction with the Air Force Flight Test Center at the Edwards AFB

During the first year of funding, we have had three meetings at the University of Colorado at Boulder with three representatives of the Flight Test Center at the Edwards AFB. During these meetings, we have reported on our progress, communicated our findings and conclusions, discussed technical details, and improved our understanding of some important issues related to our research and Air Force technical needs in these areas. We have also been in permanent contact with Flight Test Center personnel by phone and e-mail to acquire flight test and other data, and various grids and models.

3. Future work

Next, we plan to focus on the following activities:

Towards real time flutter analysis. The behavior of the fluid can be uniquely characterized by the Mach number and the angle of attack. Furthermore, using the approach advocated in the original proposal (Section 2.1.4), one can completely characterize the aerodynamic forces acting on an aeroelastic system by computing a specific set of canonical functions. Once these functions are determined for a given Mach number and a given angle of attack, the eigen solutions of the coupled aeroelastic problem can be computed for any value of the altitude, speed of sound, and any distribution of the structural mass and stiffness. Hence, we are currently working on developing the strategy for precomputing the canonical functions, expanding them for various Mach numbers and angles of attack using a discrete or other approximate form such as least-square fitting with exponential series or storing them using a compressed Laplace transform. Then, we will exploit them as needed to compute the eigen solutions of a target aeroelastic problem. Next, we plan to investigate two approaches for handling in real time changes in the Mach number and the angle of attack: a sensitivity based scheme, and curve fitting.

Continuous parameter identification of an F16 aeroelastic system. Motivated by our success for the F16 typical wing section, we are currently planning our simulations of the continuous parameter identification of an accelerating aeroelastic system for complete F16 (three-dimensional) configurations, with maneuvers.

4. Publications that have resulted from the first year of support

1. M. Lesoinne and C. Farhat, "A CFD Based Method for Solving Aeroelastic Eigenproblems in all Flight Regimes," *Journal of Aircraft*, (submitted for publication)
2. M. Lesoinne, M. Sarkis, U. Hetmaniuk, and C. Farhat, "A Linearized Method for Extracting Eigen Solutions of Aeroelastic Systems," *Computer Methods in Applied Mechanics and Engineering*, (in press)
3. X.-C. Cai, C. Farhat and M. Sarkis, "A Minimum Overlap Restricted Additive Schwarz Preconditioner and Applications in 3D Flow Simulations," *Contemporary Mathematics*, Vol. 218, pp. 478-484 (1998)
4. M. Lesoinne and C. Farhat, "Re-engineering of an Aeroelastic Code for Solving Eigen Problems in All Flight Regimes", ed. by K. D. Papailiou, D. Tsahalis, J. Périaux, C. Hirsch, and M. Pandolfi, *Computational Fluid Dynamics' 98, Proceedings of the Fourth European Computational Fluid Dynamics Conference*, Athens, Greece, pp. 1052-1061 (1998)
5. D. Rixen, C. Farhat, and L. Peterson, "Simulation of the Continuous Parametric Identification of an Accelerating Aeroelastic System," *37th Aerospace Sciences Meeting and Exhibit*, Reno, Nevada, January 12-15 (1999)